

Method Article

INTERFACE BETWEEN HYDROPOWER GENERATION AND OTHER WATER USES IN THE PIABANHA RIVER BASIN IN BRAZIL

ABSTRACT

There is an increasing need in the field of water resources management to study ways to harmonize multiple user demands. This study investigates the interface among various users of the Piabanha River Basin in Rio de Janeiro state, in particular the implications on the electricity sector of increasing upstream consumption by other water users. To estimate future losses of generation capacity in function of growing use of water resources, we applied a mathematical model called System for Simulation of Power Plants with Consumptive Water Uses (Sis-UCA in the Portuguese abbreviation), considering both the existing power plant cascade and the likely future configuration with the inclusion of new projects under construction and in the planning phase, along with projections for future water demand by other users. There was some difficulty obtaining data about the basin, but this did not impair validation of the model, which converged to results that provide support for shared management of multiple water uses. Among the results attained, it is possible to state that 75% of the maximum usable water is already being utilized, leading to the conclusion of likely water conflicts in the near future.

Keywords: **Hydropower and electricity generation**, SisUCA, Piabanha River Basin, modeling.

1 INTRODUCTION

Quantity and timing of water needs affects the relationship of different types of users (Pitana, 1993). Estimation of growth in total water demands relies on the understanding of the underlying social, economic, and environmental drivers to changes in sectoral water demands (Hejazi *et al.* 2014). When changes in water rights lead to changes in access some users will also experience scarcity and water users who once had adequate water for their needs, no longer have access to quantities and quality of water which they need. Water scarcity challenges existing property rights systems which were able to allocate water under conditions of surplus. (Meizen-Dick and Jackson, 1996)

According to Tucci *et al.* (2001), the development of water resources and preservation of natural systems are major challenges for Brazilian society and include various aspects related to social and economic conditions. Among the challenges for sustainable use of water resources are institutional aspects, regional development versus

40 environmental preservation needs and training of human resources.

41 In Brazil, Federal Law 9,433/1997, known as the Water Law, establishes the basic
42 framework for water resource allocation, determining that the management of water
43 resources must promote multiple uses in decentralized form, with participation of all
44 stakeholders. According to its Article 12, authorization is required for any use of water
45 resources that can alter the regime, quantity or quality of a determined water body.
46 Furthermore, in situations of shortage, supply to humans and livestock must come first.
47 Since water demands for a wide range of uses have been increasing, conflicts are also
48 becoming more pressing.

49 River basin inventory studies are considered strategic since they constitute the
50 first stage of a hydropower project planning cycle of (Pires, 2008). The watershed
51 analyzed here is that of the Piabanha River. It is relevant since together with the
52 Paraibuna River it provides the initial contribution to the flow of the Paraíba do Sul
53 River after transposition, by pumping, from Santa Cecília Reservoir, which reduces the
54 net flows in the downstream segment starting in the municipality of Barra do Pirai
55 (CEIVAP, 2006). This basin's problems are similar to those of many other Brazilian
56 watersheds: lack of basic sanitation infrastructure, expanding secondary sector (e.g.,
57 textile and beverage industries) and aggravation of water use conflicts. There are several
58 small hydroelectric plants (abbreviation: SHPs) along the Piabanha River and its
59 tributaries, some in operation for over a century, and new ones are either under
60 construction or in the planning stage.

61 Global electricity demand has grown by a factor of four since 1970, and
62 international agencies and integrated assessment models anticipate continued growth
63 into the future, driven in large part by increasing population and per-capita income.
64 (Davies *et al*, 2013)

65 More than 82% of Brazil's electricity is hydropower, despite efforts to diversify
66 supply by building thermal plants and wind farms, making the country highly dependent
67 on this energy source (EPE, 2012). However, COSTA et al. (2011) mention that only
68 30% of Brazil's potential is explored, converging with IEA (2011), which reveals that
69 the global hydropower potential is 2-3 times higher than the current generation, with the
70 greatest potential to be developed in Africa, Asia and Latin America. Although
71 hydropower plants do not consume water, the operation of the reservoir can affect both
72 upstream and downstream users, causing conflicts of interests between generation of
73 power and satisfaction of other demands.

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¹ The municipality is the local political unit in Brazil, and is similar to a county except that there is a single mayor and municipal council. Large metropolitan regions typically cover several municipalities while in rural regions a municipality may have only one or a few small towns. There are no unincorporated areas in Brazil.

The river's headwaters are located in the Órgãos Range and they drain toward the middle part of the Paraíba do Sul River Valley. The river passes through Petrópolis (population of about 300 thousand), the largest city in the mountain region of Rio de Janeiro. After Petrópolis, the river flows to the north, passing through the town of Areal and continuing for a further 80 km until emptying into the Paraíba do Sul River on its right bank in the town of Três Rios.

The Piabanha River on its left margin receives water from the Araras and Fagundes rivers, while on the right bank its tributaries are the Quitandinha, Palatinado, Itamarati, Poço do Ferreira, Santo Antonio and Preto rivers. The basin suffers from environmental and civil defense problems such as poor water quality, landslides, flooding and irregular occupation along the margins of the main rivers (as shown in Photo 1, taken on November 21, 2013), in the last case due to the influx of people who cannot afford better housing.



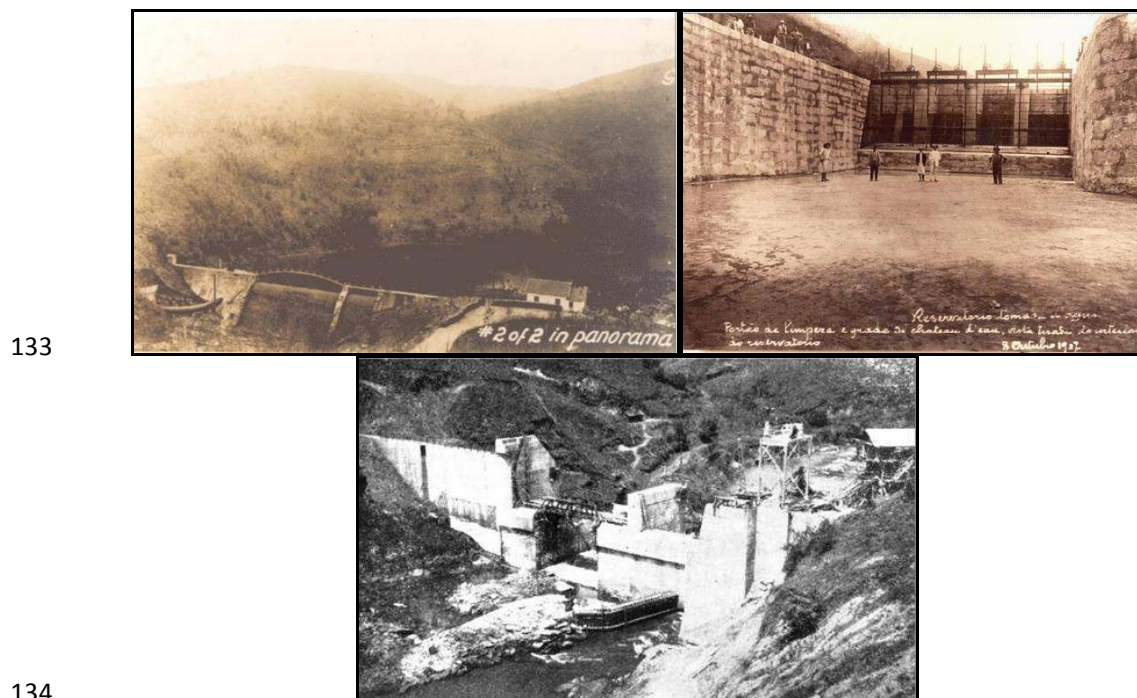
Photo 1: Irregular dwellings built along the river. Source: Authors.

2.1 Current authorized users of water from the basin

The list of authorized users of water in the basin was obtained from the Piabanha Watershed Committee. The total authorized flow captured is 25.275 m³/s, of which the user holding the largest allotment is Poço Fundo Energia S/A, the company that has the concession to build and operate the Poço Fundo SHP, with a non-seasonal permit to

draw 22.550 m³/s. Since hydropower generation does not consume water, it can be inferred that the overall official figure does not reflect the consumptive uses in the basin, which are on the order of 2.725 m³/s. Besides this, the numbers do not include the water drawn by the municipalities that are not within the Piabanha River Basin, in the total amount of 0.170 m³/s. Therefore, we assumed the consumptive uses represent a flow of 2.555 m³/s.

Besides the Poço Fundo SHP, which is still under construction, the basin has three other small hydropower installations: Piabanha SHP, in operation since 1908, located at the confluence with the Preto River; Morro Grande or Areal SHP, located on the Preto River near where it flows into the Piabanha River, in operation since 1949; and Coronel Fagundes SHP, located along the final segment of the Fagundes River, operating since 1924. Besides these, plans call for building three more SHPs on the Piabanha River (Posse, Monte Alegre and São Sebastião); one on the Preto River (Providência, besides Poço Fundo); and one on the Capim River (Capim SHP), which is a tributary on the right margin of the Preto River. There are also plans to expand the installed power of Piabanha SHP from 9 MW to 18.1 MW (PLANAVE e GUASCOR, 2001). Figure 2 depicts the basin's topology with its main tributaries and the location of the existing (in green) and future (in red) hydroelectric installations, along with the respective drainage areas.



Photos 2 to 4: Constructions of dams from SHPs Coronel Fagundes, Piabanha and Morro Grande respectively. Source: ME, 2000.

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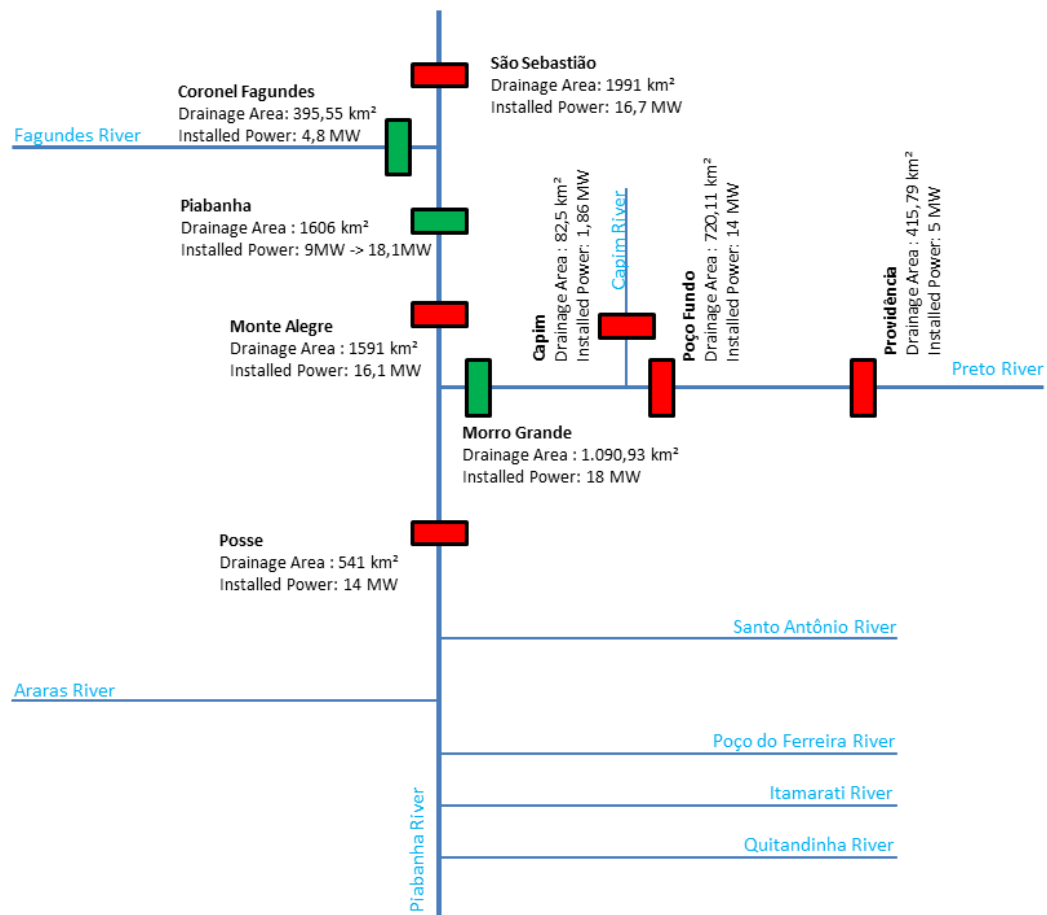
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Photos 5 to 7: SHPs Coronel Fagundes, Morro Grande and Piabanha nowadays respectively.
Source: Authors.



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Figure 2: Topology with the power plants in operation and future undertakings.

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3 METHODOLOGY

147 To assess the hydropower generation in the basin and its harmonization with other
148 growing water uses, we applied the SisUCA mathematical model, developed by Hora
149 (2015), which employs the formulation developed in the MSUI (Model for Simulation of
150 Individualized Power Plants), in turn developed by Eletrobrás, with the introduction of a
151 new variable corresponding to the water diverted, with the total withdrawals being
152 limited by the maximum licensable flow (*vazão máxima outorgável*, or VMO).

153 The VMO represents the flow available for use and is limited by the water
154 available from the watercourse without jeopardizing its ecological state. In the state of
155 Rio de Janeiro, the State Environmental Institute (INEA), manager of water resources,
156 sets the VMO at 50% the $Q_{7,10}$, which represents the minimum seven-day flow in a ten-
157 year return time. In the case of the Piabanha River, the VMO values were calculated
158 from the regional equation defined in CPRM (2003), expressed by:

$$159 \quad Q_{7,10} = 0.0419 \cdot A^{0.6728} \quad (1)$$

$$160 \quad Q_{7,10} = 0.0419 \cdot A^{0.8427} \cdot P^{2.4246}, \text{ equation suggested for the Fagundes River (2)}$$

161 where:

162 $Q_{7,10}$ minimum seven-day flow in a ten-year return time, in m^3/s .

163 A drainage area, in km^2 .

164 P average annual rainfall, in m. For the Fagundes Sub-basin, CPRM (2003)
165 suggests a value of 1.352 m.

166 For the SHPs for which no historic flow series are available (Morro Grande/Areal,
167 Coronel Fagundes, Providência and Capim), we defined these series based on the flows
168 observed at the gauging stations located on the same river and/or the flow series from
169 the nearest power plants. Therefore, for the Morro Grande/Areal and Providência SHPs,
170 we used the correlation of drainage areas with Poço Fundo SHP and for Coronel
171 Fagundes SHP we generated the series from the flows measured at the Fagundes
172 gauging station and at Posse SHP. Finally, for Capim SHP we used the correlation with
173 Providência SHP.

174 With respect to the physical and hydraulic characteristics of the power plants, for
175 the yield of the turbine-generator set of those without available data (Providência,
176 Coronel Fagundes and Morro Grande/Areal), it was adopted the value of 0.90, which
177 corresponds to the product of the individual yields of the turbine (0.93) and generator

178 (0.97) (Eletrobrás, 2007).

179 To calculate the maximum turbinable flow (Q_{turbmax}), we used the expression
180 defined by Eletrobrás (2007), represented by:

$$181 \quad Q_{\text{turbmax}} = \frac{PI_i \cdot 1000}{9.81 \cdot \eta_i \cdot h_{\text{ref}_i}} \quad (3)$$

182 where:

183 PI_i installed power of plant i, in MW.

184 h_{ref_i} rated head of plant i, in m.

185 η_i efficiency of the turbine-generator-transformer system.

186 With respect to water losses, Eletrobrás (2007) recommends adoption of a value
187 of 2% of the respective gross hydrostatic heads. The gross head is the difference
188 between the normal maximum water level in the reservoir and the normal maximum
189 water level downstream of the dam at the turbine outlet. The reference head is
190 calculated, in the case of SHPs, by the difference between the gross head and the water
191 losses (Eletrobrás, 2007). The evaporation values were calculated by using the
192 spreadsheet developed by Noronha (2011).

193 To assess the power generation losses due to growing water consumption by other
194 users in the Piabanha River Basin, we defined two scenarios: the first with the current
195 arrangement of the power plants in operation (Piabanha, Morro Grande/Areal and
196 Coronel Fagundes), called the current one, and the second also including the plants
197 under construction/expansion or planned for the coming years (expanded Piabanha,
198 Posse, Monte Alegre, São Sebastião, Morro Grande/Areal, Capim, Poço Fundo,
199 Providência and Coronel Fagundes), called the future scenario. In both simulation
200 scenarios, we considered the water demands for other uses in the basin together with
201 operation of the reservoirs. The demand scenarios, limited to the VMO value, were
202 additional water removals of 0%, 25%, 50%, 75% and 100% of the VMO.

203 The evaluation of energy generation and losses associated with growing water
204 consumption by other users was defined starting by comparing the average and firm
205 power generation of each plant individually and of the entire set (cascade), considering
206 the average monthly series corresponding to the period from January 1931 to
207 December 1999. The average energy resulted from the simulation for the entire period
208 and the firm energy resulted from the average value of the simulation for the critical
209 period of the Brazilian electric power system (June 1949 to November 1956). This
210 period corresponds to the most unfavorable hydrological period faced by Brazil.

211 Finally, the average and firm energy generation is expressed in the model
 212 (Eletrobas, 2007) by:

$$213 \quad Em_i = 0.0088 \cdot h_{ref,i} \cdot Q_i \quad (4)$$

$$214 \quad Ef_i = 0.0088 \cdot h_{ref,i} \cdot Q_{crit,i} \quad (5)$$

215 where:

216 Em_i is the average energy generation in plant i , in MWmonth;

217 Ef_i is the firm energy generation in plant i , in MWmonth;

218 $h_{ref,i}$ is the reference head in plant i , in m;

219 Q_i is the monthly operating flow in plant i , m^3s^{-1} ;

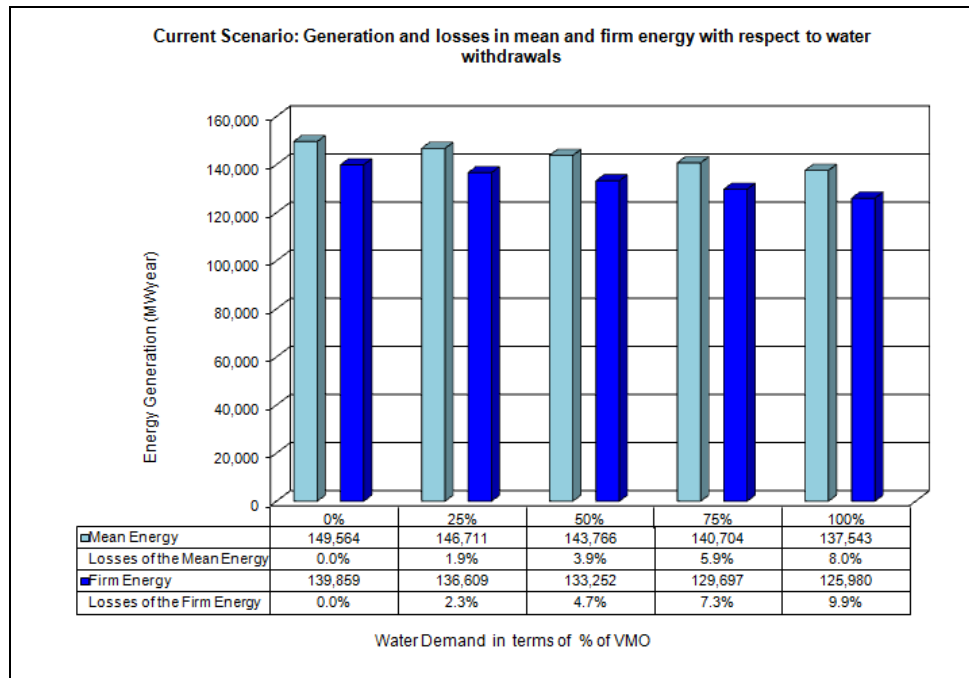
220 $Q_{crit,i}$ is the monthly operating flow in plant i , in the critical period (June 1949 to
 221 November 1956), in m^3s^{-1} ;

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223 4 RESULTS & DISCUSSION

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225 Figures 3 and 4 present, respectively, the result attained from the simulations of
 226 average and firm energy levels as well as the losses in generating capacity related to
 227 increased allocation of the VMO for the current and future scenarios.



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229 **Figure 3: Comparison between average and firm energy generation in the current scenario**

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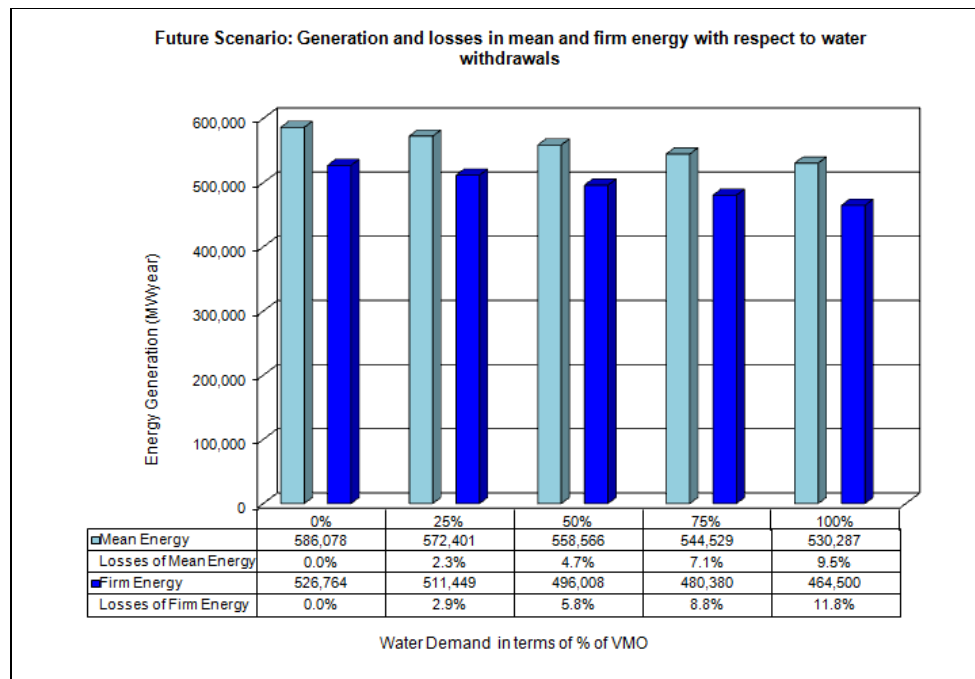


Figure 4: Comparison between average and firm energy generation in the future scenario

It should be noted that during the simulations, we found negative incremental flow values for some of the power plants. This can mean inconsistency in the average monthly flow series, as pointed out by Hora (2015). Nevertheless, we decided to maintain the flow series defined in the inventory, because of its approval by ANEEL. Table 1 presents the number of occurrences of negative incremental flows resulting from the simulations in both scenarios.

Table 1: Number of occurrences of negative incremental flows

Current Scenario	Piabanha SHP with 114 occurrences
Future Scenario	Monte Alegre SHP with 801 occurrences
	São Sebastião SHP with 546 occurrences

Analysis of the energy loss results shows that the plants with lowest installed capacity (Providência, Capim and Posse) presented the largest losses due to increasing water consumption by other users, with the standout being Capim SHP, for which the loss was around 22% in both scenarios.

Nevertheless, in general all the power plants will face generation losses with increase of the VMO allocation to other users. These estimated losses are between 1.3 and 19% for average energy production, and between 2.1 and 22% for firm energy generation.

Given that the uses in the basin total 2.555 m³/s and the VMO of São Sebastião

250 SHP (located near the point where the Piabanha River flows into the Paraíba do Sul
251 River) is equal to 3.48 m³/s, nearly 75% of the basin's VMO is already being utilized,
252 representing losses of potential power generation of 5.92% for average energy and
253 7.27% for firm energy.

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255 5 CONCLUSIONS

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257 The average monthly flow series defined in the inventory studies and approved by
258 ANEEL present problems related to incremental flows. We recommend review of the
259 average monthly flows of all the hydroelectric plants, already operating, under
260 construction and planned in the Piabanha River Basin.

261 The results of applying the SisUCA model converged in all the water removal
262 scenarios, allowing inferring that it is a valid tool to analyze generation losses due to
263 multiple water uses in the Piabanha River Basin.

264 The current water uses account for approximately 75% of the VMO at the river
265 mouth, which already represents an energy loss for the current scenario. This can
266 compromise satisfaction of power demand contracted for the new undertakings and
267 signals a perspective for conflicts, since the trend is for the VMO to be totally used in
268 the not-too-distant future. This tendency is aggravated by the current situation
269 associated with the historic problems due to low water availability in a region with
270 considerable population density. Therefore, further studies are needed to assess the
271 impact on energy generation and economic performance from reduction of flows to the
272 power plants not yet constructed, as well as the inclusion of discussion of this theme on
273 the agenda of the Piabanha River Basin Committee, to minimize possible water use
274 conflicts.

275 Therefore, this study becomes an important tool for decision making of both
276 government and civil society about the future of this region and also provides to the
277 society the ratification of a solid model that can be applied in other areas where disputes
278 over water between users and the hydroelectric sector already are present or can be seen
279 in potential.

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